A new method of observing weak extended x-ray sources with RHESSI

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(Dated: February 9, 2007)

We present a new method, fan-beam modulation, for observing weak extended x-ray sources with the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI). This space-based solar x-ray and γ-ray telescope has much greater sensitivity than previous experiments in the 3-25 keV range, but is normally not well suited to detecting extended sources since their signal is not modulated by RHESSI's rotating grids. When the spacecraft is offpointed from the target source, however, the fan-beam modulation time-modulates the transmission by shadowing resulting from exploiting the finite thickness of the grids. In this paper we detail how the technique is implemented and verify its consistency with sources with clear known signals that have occurred during RHESSI offpointing: microflares and the Crab Nebula. In both cases the results are consistent with previous and complementary measurements. Preliminary work indicates that this new technique allows RHESSI to observe the integrated hard x-ray spectrum of weak extended sources on the quiet Sun.

PACS numbers: 95.55.Ev,95.55.Ka,95.75.-z

I. INTRODUCTION

The Reuven Ramaty High-Energy Solar Spectroscopic Imager, RHESSI [1], is a space-based solar x-ray and γ-ray telescope that was launched in 2002. Its main goal is to obtain spectroscopic and imaging information of solar flares with high time and energy resolutions from 3 keV to 15 MeV. In particular it has unprecedented sensitivity for 3-25 keV x-rays. This is because when its automated attenuators (used in flare observations) are "out", it can observe down to the nominal 3 keV limit with the full area of the detectors, something not possible for earlier instruments which used fixed shielding to prevent excessive counting rates from soft x-rays in flares. Normal RHESSI imaging is accomplished with a set of nine bi-grid rotating modulation collimators (RMCs) with resolutions logarithmically spaced from $2.3''$ to $183''$. Each RMC time-modulates sources whose size scale is smaller than their resolution. Thus despite its sensitivity, it is not well suited to observe weak sources larger than 3 arcminutes. For weak sources it is also essential to distinguish counts due to photons from the target from those due to terrestrial, cosmic or instrumental background.

To achieve this we have developed a technique called *fan-beam modulation*, detailed and tested in this paper, that involves pointing the telescope slightly away from the target. As RHESSI rotates, the narrow field of view ($\sim 1^\circ$ FWHM) of RHESSI's thick grids time-modulates the signal to "chop" between an extended source and background.

The main motivation for developing this technique is to obtain the hard x-ray spectrum of the Sun free of sunspots, active regions and flares (the quiet Sun). We expect the quiet Sun sources to be weak and well-dispersed across the solar disk (the diameter of which is about $32'$) . Since hard x-ray instrumentation is typically optimized for flare observations (bright compact sources), such quiet Sun observations remain an elusive measurement despite interest back to the earliest days of solar x-ray observations [e.g., 2]. With RHESSI we have the possibility of improving these values as well as extending them to lower and higher energies.

The focus of this paper is to introduce the *fan-beam modulation* technique, whose implementation is explained in Sec. II. In Sec. III we test this method on sources with strong or well-known signals: microflares that occurred during quiet Sun offpointing, and the Crab Nebula. In Sec. IV we present some analysis from periods of low solar activity, illustrating that this method is capable of observing weak extended sources.

II. RHESSI OFFPOINTING

The RHESSI telescope consists of nine pairs of grids in front of nine germanium detectors [1], which record x-rays with high energy and time resolution from 3 keV to 15 MeV. To obtain temporal modulation of the counting rates the spacecraft rotates about the axis pointing at the Sun with a rotation period of about 4 seconds. Each pair of grids then constitutes a rotating modulation collimator, RMC [3]. Compact sources on the solar disk (such as flares) are rapidly time-modulated by the grids, enabling high-resolution imaging, but the primary modulation of solar-size sources is negligible.

There is, however, a secondary modulation that results from the finite thickness of the collimator grids [4]. This "envelope" modulation peaks twice every rotation

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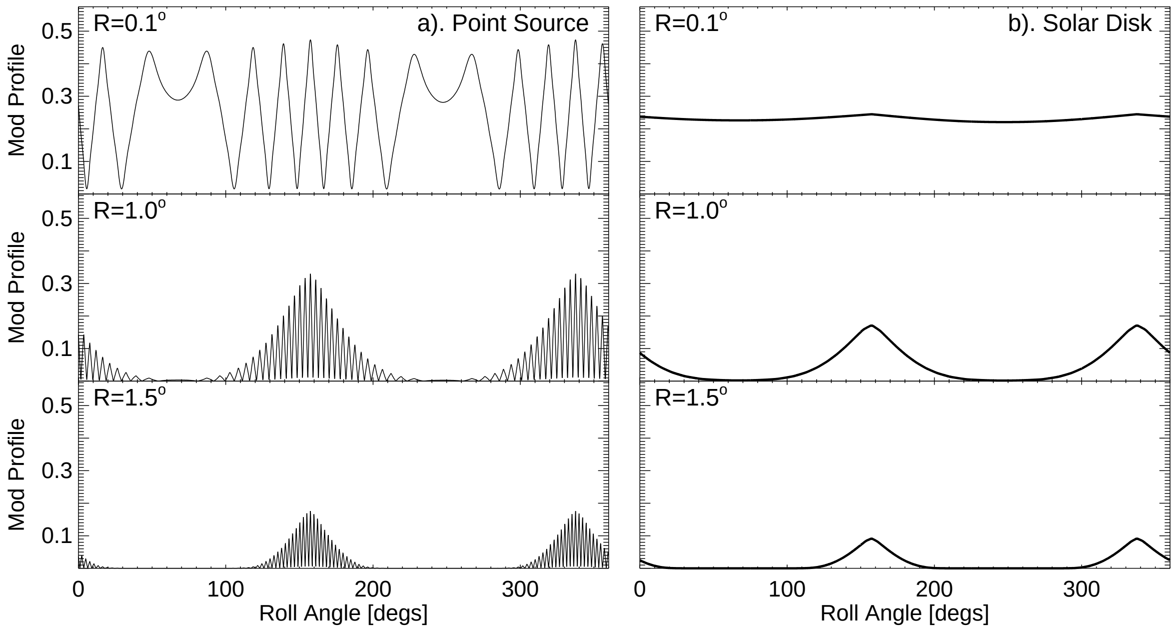

FIG. 1: The expected modulation profile of a a). point source and the b). solar disk through one of RHESSI's rotating collimators, for three different radial offsets between RHESSI pointing and source center. Normal RHESSI imaging is based on the rapid modulation in the left panel.

when the slits of the grids are parallel to the line between RHESSI pointing and source center, producing two transmission maxima per rotation. For one collimator, Fig. 1 shows the expected modulation profiles for a point source and for the solar disk as a function of roll angle for several off-axis angles. The top row of this figures shows the result for typical solar pointing: a point source has the expected rapid modulation, but this does not occur for the full solar disk. As the offpointing angle increases the frequency of the rapid modulation increases as well as the secondary fan-beam modulates the signal twice per rotation.

The fan-beam modulation increases with the offpointing angle as shown in Fig. 2, where we have plotted its amplitude as a function of radial offset. For this work we do not use the data from RMCs 2, 5 or 7 since their thresholds are above 3 keV and/or have degraded energy resolution. The first four RMCs shown have the smallest field of view ($\sim 1°$) orthogonal to the slits and so the modulation is greater than in RMCs 8 and 9, whose FOV is $\sim 8°$ and $\sim 3°$ respectively. Fig. 2 also shows that we get the maximum effect of the fan-beam modulation technique when RHESSI is pointing between $0.4°$ and $1°$ away from source center. At larger angles the increasing shadowing of the grids on the detectors reduces the amplitudes. Normally the RHESSI pointing control system remains inactive when its rotation axis is within a dead-band corresponding to solar offsets between $0.05°$ and $0.2°$. To initiate offpointing the dead-band limits are changed to $0.4°$ and $1.0°$. For quiet Sun observations, this mode of operation has been initiated several times when the GOES soft x-ray flux was low and no active regions or

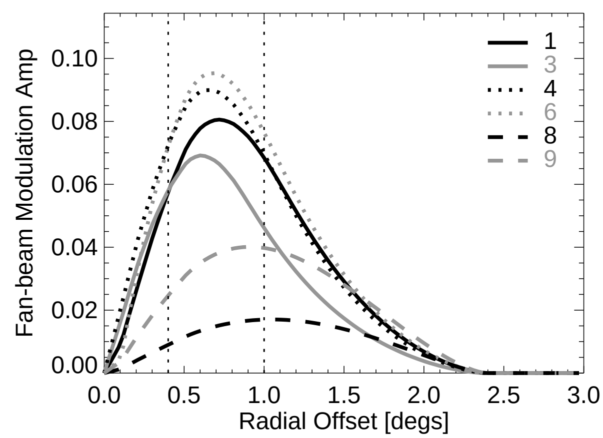

FIG. 2: The fitted amplitude of the fan-beam modulation (for a uniform solar disk) as a function of radial offset from the target. The modulation is maximised at offsets from $0.4°$ to $1.0°$.

spots were on the disk. A summary of RHESSI's pointing and the GOES flux during the October 2005 offpointing is shown in Fig. 3.

To facilitate the analysis of such a large data set it is divided into successive five-minute time intervals, which are short enough that the pointing of the spacecraft changes little. The data for each five-minute interval can be analyzed in any energy range above 3 keV, although smaller energy bands provide poorer statistics. For a chosen energy range we bin ("stack") the data according to the roll

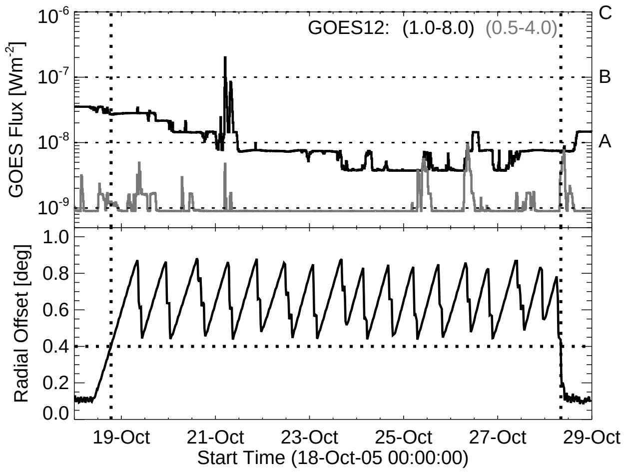

FIG. 3: Summary of RHESSI offpointing during October 2005. The top panel shows the GOES-12 x-ray flux in the 1-8Å and 0.5-4Å channels, the bottom panel the radial offset of RHESSI pointing from Sun center.

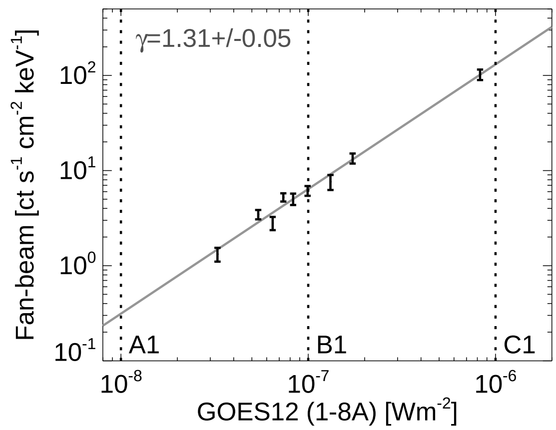

FIG. 4: The mean counts flux in 4-6 keV obtained using the fan-beam modulation technique for nine microflares occurring during quiet Sun offpointing, compared to the background subtracted GOES 1-8Å flux.

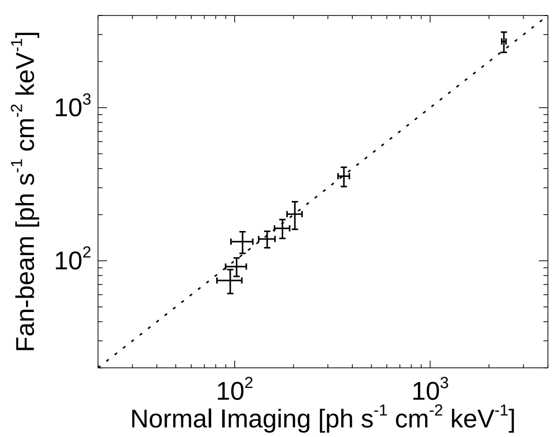

FIG. 5: Comparison of the mean 4-6 keV photon flux, obtained using the fan-beam modulation technique, and the photon flux found through a normal RMC9 back-projection image, for 8 microflares (imaging was not possible for one of the 9 microflares shown in Fig. 4).

angle, θ, for each subcollimator, correcting for the relative geometry of the spacecraft pointing and the source and the grid orientation such that $\theta = 0$ when the grid slits are aligned to the source. We then fit this stacked data with

$$F(\theta) = A_0 + A_1 \cos(2\theta + \phi_1) + A_2 \cos(4\theta + \phi_2), \quad (1)$$

where A_0 is the background term, A_1 and A_2 are the main and first harmonic amplitudes of the signal and ϕ_n are the fitted phases. The source signal should occur at 0° and 180°, with the phase offset ϕ should be zero, as we have corrected θ. The A_1 amplitude then provides the measure of the source flux although it has to be corrected for the grid transmission efficiency and grid shadowing, factors dependent on radial offset shown in Fig. 2. After this correction, the resulting fits from different time intervals can then be combined vectorially to improve the signal-to-noise ratio before conversion to a final photon flux. This conversion is achieved by either using the diagonal elements of the appropriate detector response matrix [5], or via forward-fitting a model to the spectrum using the full detector response matrix in the OSPEX software package (an updated version of the SPEX code written by R. Schwartz).

III. TESTING THE OFFPOINTING PROCEDURE

We test the fan-beam modulation technique on microflares which have a relatively large signals, and the Crab Nebula, an extended source whose weaker signal is well known.

A. Microflares

Several microflares occurred during quiet sun offpointing intervals. One typical event occurring at 22:33:00 25 July 2005 was equivalent to a GOES A8.3 flare with background subtracted. One minute of 4-6 keV stacked data for this event is shown in Fig. 6. In RMCs 1, 3, 4 and 6 we get a strong and clearly defined signal, which matches the expected modulation. In RMCs 8 and 9 the modulation is not as strong, as expected from Fig. 2. Making the grid transmission correction to the amplitude fit of the signal in RMCs 1, 3, 4 and 6 we average the four fluxes to obtain a single value for this flare in the 4-6 keV band.

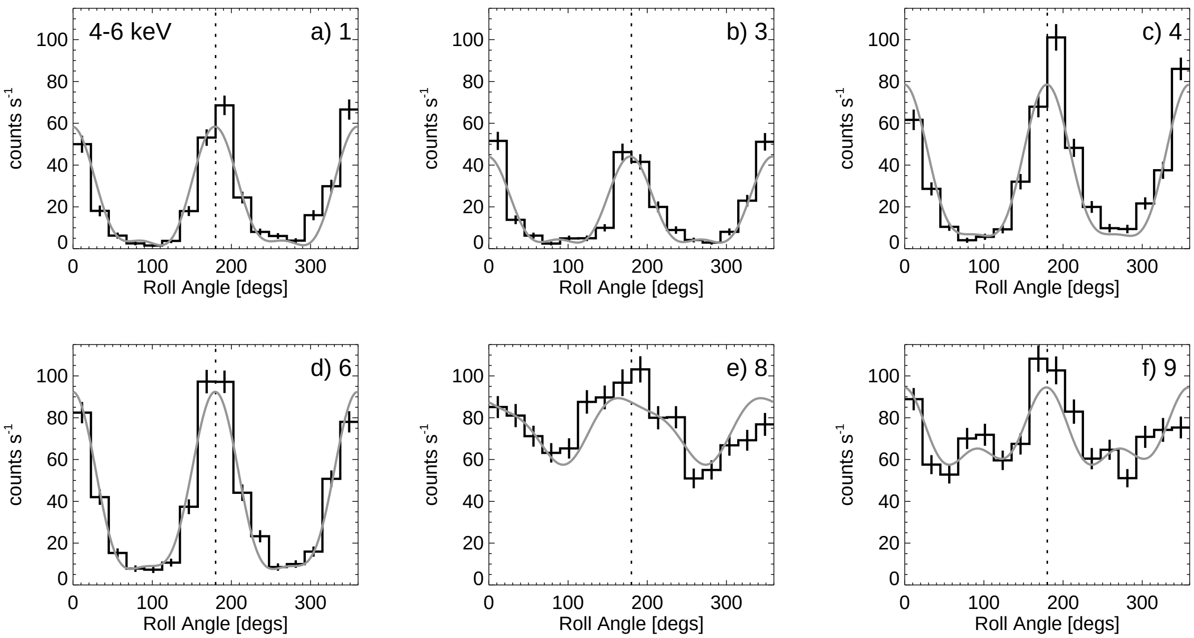

FIG. 6: The stacked RHESSI counts in 4-6 keV through each suitable subcollimator for an A8.3 microflare. In this fit we have included the first harmonic as well as the fundamental term. Since the roll angle has been corrected for the orientation of the grids and relative positions of RHESSI pointing and the microflare, the signal should peak at 0° and 180°.

This analysis was repeated for each of the nine microflares for which we achieved good coverage during our four quiet-Sun offpointing periods. Fig. 4 shows the RHESSI 4-6 keV microflare counts, corrected for grid transmission, against the corresponding GOES 1–8Å energy fluxes. The errors shown for the values derived from the fan-beam modulation are based on the standard deviation of the values found from each of the four individual detectors. This systematic error among the detectors (about 13.5% for these microflares) is larger than the statistical error found from each of the fits. This systematic discrepancy is a known issue with RHESSI and is still under investigation. The correlation between the RHESSI and GOES fluxes shown in Fig. 4 is an excellent fit to a power law but differs from unity (power-law index 1.33). This may reflect temperature differences among flares convolved with the difference between the GOES and RHESSI spectral response.

When RHESSI is offpointed from the Sun, pitch and yaw information is obtained from the Fine Sun Sensor (FSS) which is intrinsically less precise than the Solar Aspect System (SAS) used for conventional RHESSI imaging. However its accuracy is more than sufficient to support fan-beam modulation analyses as well as conventional back projection imaging with the coarsest subcollimator, RMC9. The agreement between conventional imaging and the fan-beam modulation technique is illustrated in Fig. 5 which shows a comparison of the 4-6 keV fluxes.

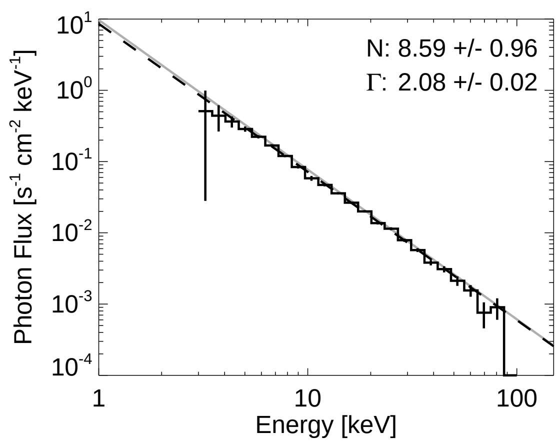

FIG. 7: The spectrum of the Crab found using the fan-beam modulation technique (histogram). The dashed black line is a powerlaw fit to the data between 4 and 60 keV. The grey line is the reference spectrum from Toor and Seward[8].

B. Crab Nebula

In an annual program, RHESSI points away from the Sun to image the Crab Nebula and pulsar, around the time of the Sun's closest approach (mid-June). Since the hard x-ray spectrum of the Crab is well-known and stable [6] it provides a photometric test of the fan-beam modulation offpointing technique.

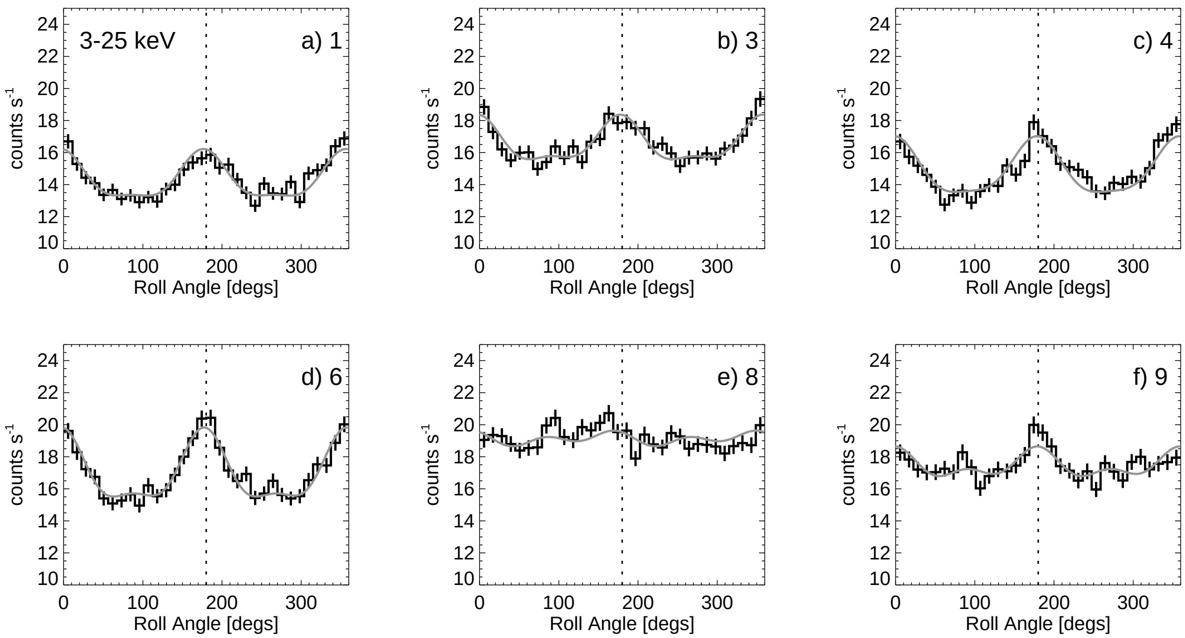

FIG. 8: The stacked 3-25 keV RHESSI counts for an hour-long integration during Crab offpointing in June 2004. The roll angle has been corrected for the orientation of the grids and relative positions of the Crab and RHESSI pointing, so that the Crab signal should be at 0° and 180°. The continuous line shows the model fit for a point source at the location of the Crab Nebula. This data have not been corrected for grid dependent parameters such as thickness.

In the 2004 campaign, some data were taken at radial offsets suitable for testing the fan-beam modulation technique (the Crab between 0.4° and 1° away, the Sun $> 2.5°$). As a result the Crab signal is modulated while the Sun is too far away to be directly observed. Thus even in the presence of solar activity we can obtain a clean Crab signal. From 11 to 20 June 2004 this orientation occurred for a total of 19 such orbits (each about an hour in length), avoiding times of high particle background during the South Atlantic Anomaly (SAA) passages.

The stacked counting rates in the 3-25 keV band for one of these orbits is shown in Fig. 8. As before the roll angles are corrected for the grid orientation and the relative position of the Crab to RHESSI pointing, so that the Crab signal should occur at 0° and 180°. Fig. 8 shows the stacked signal for six of the RHESSI detectors. In RMCs 1, 3, 4 and 6 we get the expected modulation which is fitted well by Eq. 1 (shown as a grey line).

For each of the four detectors we fit the stacked count-rate data for each orbit in a series of energy bands from 3 to 100 keV. The amplitude of these fits is corrected for the grid transmission for the particular radial offset of that orbit. This provides a count spectrum, corrected for grid transmission, for each of the four detectors. Then each of these spectra is forward-fitted using the OSPEX software package [7] with a power law and the appropriate detector response matrix, to obtain a photon spectra. The four photon spectra and their fits are then combined and shown in Fig. 7.

Fitting a power law $dN/dE = NE^{-\Gamma}$ ph s^{-1} cm^{-2} keV^{-1}, we obtain $N = 8.59 \pm 0.96$ and $\Gamma = 2.08 \pm 0.02$, for the RHESSI data between 4 and 60 keV, as shown in Fig. 7. The standard values for these parameters are $N = 9.7 \pm 1.1$, $\Gamma = 2.1 \pm 0.03$ for the range 2–50 keV [8]. The consistency with our observations provides confidence in their photometric accuracy. Comparison with a more recent survey of these parameters also provides similar results [6].

IV. TEST ON THE NON-FLARING SUN

Here we present a preliminary analysis of the quiet Sun signal, to indicate that this method works on the intended target source.

For this analysis we have used the data from the four initial quiet Sun offpointing periods, as detailed in Sec. II and illustrated in Fig. 3. During this period the Sun was very quiet with the GOES 12 flux in 1-8Å "flat-lining" below 10^{-8} Wm^{-2}. We do not use the full offpointing periods in the analysis; instead we screen the time intervals by checking the RHESSI data for sharp time-series features (such as flares or particle events). We have also restricted the data to times when RHESSI is at the lowest latitudes in its orbits, to minimize the terrestrial background. From these four offpointing periods we have a total of 1,522 five-minute time intervals (over 126 hours

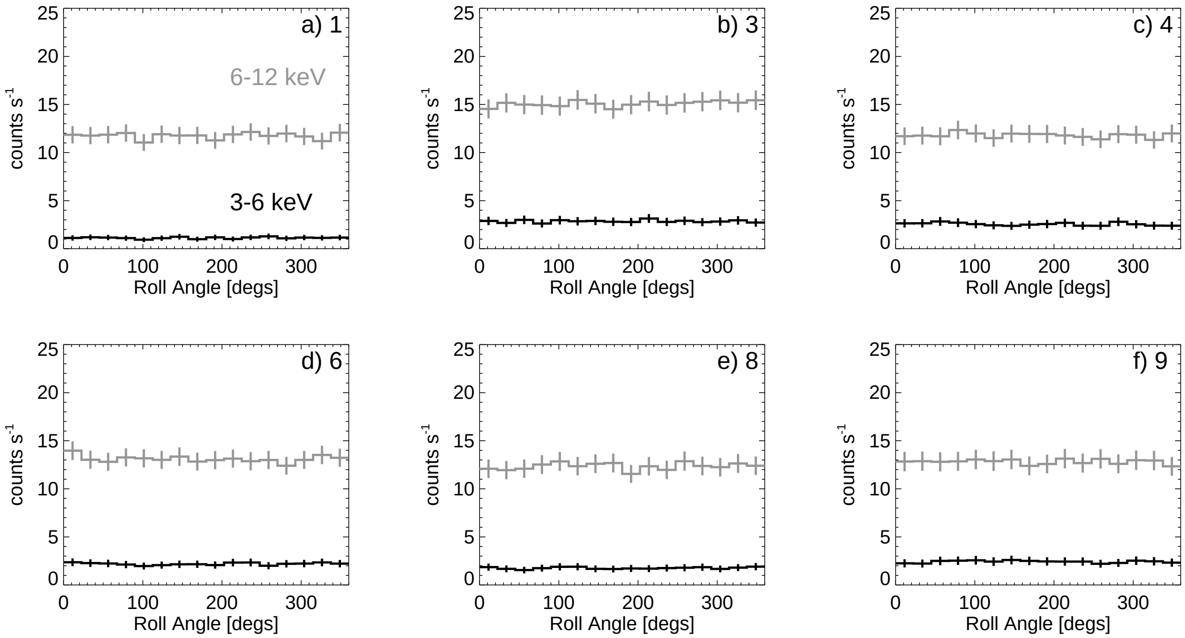

FIG. 9: The stacked RHESSI counts through each suitable subcollimator for 1 hour of quiet Sun during offpointing. Two energy bands are shown: 3-6 keV (black) and 6-12 keV (grey). Note that the roll angle has been corrected for the orientation of the grids and relative positions of the Sun and RHESSI pointing, so that the solar signal should be at 0° and 180°.

of data).

For each of the five-minute intervals we selected a set of energy bins and fit the stacked data in each subcollimator with Eq. (1). The stacked data in two energy ranges (3-6 keV and 6-12 keV), for 1 hour of quiet Sun data, with GOES background flux below A1 level, are shown in Fig. 9. No obvious signal appears, but none would be expected. This highlights the need to combine many time intervals to improve the signal-to-noise. We fitted the stacked data from each RMC with Eq. 1 in such a way that an $A_i \cos\phi_i$ and $A_i \sin\phi_i$ term, with associated errors, is returned for each of the cosine terms in Eq. 1. Statistically the expectation value of $\langle A_1 \cos\phi_1\rangle \approx A_1$, the source signal, and $\langle A_1 \sin\phi_1\rangle \approx 0$. The former represents the measurement of interest while the latter provides a consistency check.

Fig. 10a shows the mean 3-6 keV counts (corrected for grid transmission) for each detector averaged over all 1,522 five-minute intervals. The larger error bars for RMC8 and 9 reflect their lower modulation efficiency. Although the scatter is larger than the statistics would suggest, there is a clear detection. Fig. 10b shows the corresponding average for the $\langle A_1 \sin\phi_1\rangle$ term which, as expected, is consistent with zero. In the higher 6-12 keV energy channel we achieve similar results, with the $\langle A_1 \cos\phi_1\rangle$ positive and non-zero and $\langle A_1 \sin\phi_1\rangle$ consistent with zero. These results both show that the fan-beam modulation technique works by being able to detect a signal from the non-flaring quiet Sun.

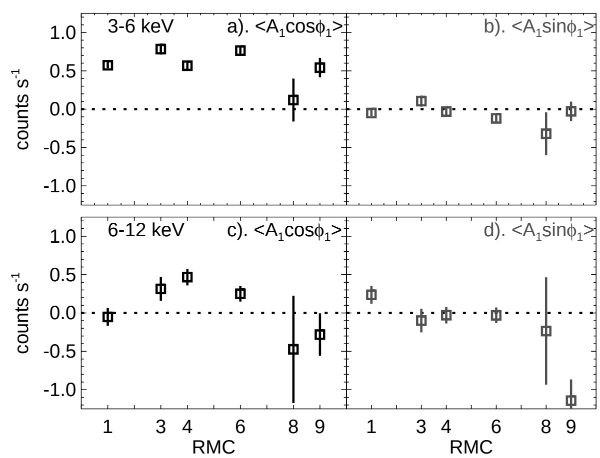

FIG. 10: The mean value of the fit components $A_1 \cos\phi_1$ (left panels, a). and c).) and $A_1 \sin\phi_1$ (right panels, b). and d).) for detectors RMCs 1, 3, 4, 6, 8 and 9, averaged over the 1,522 five-minute quiet Sun time intervals. The top row show the results for 3-6 keV, the bottom row for 6-12 keV.

V. CONCLUSIONS

We have developed a new technique for observing the quiet Sun which uses of the fan-beam collimation of the grids. The technique extends RHESSI observations to sources larger than can be imaged using conventional bi-grid modulation. As presented in Sec. III B, the photometric accuracy of the technique has been verified using the known flux of the Crab Nebula.

From the initial tests of the fan-beam modulation technique on the quiet Sun we are able to achieve positive non-zero signal. We would then expect that the fan-beam modulation technique holds promise for offpointing periods when observations in the magnetically quieter conditions expected in 2007.

Acknowledgments

NASA supported this work under grant NAG5-12878. We thank many people involved in the RHESSI program for inspiration and assistance with software, calibration, and spectral fitting issues, especially Brian Dennis, Richard Schwartz and David Smith.

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